

THE NN-FINAL-STATE INTERACTION IN TWO-NUCLEON KNOCKOUT REACTIONS

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The influence of the mutual interaction between the two outgoing nucleons (NN-FSI) in electro- and photoinduced two-nucleon knockout from ^{16}O has been investigated perturbatively. It turns out that the effect of NN-FSI depends on the kinematics and on the type of reaction considered. In the kinematics studied so far, the effect is larger in pp- than in pn-knockout and in electron induced than in photoinduced reactions.

1. INTRODUCTION

The independent particle shell model (IPM), describing a nucleus as a system of nucleons moving in a mean field, describes many basic features of nuclear structure. However, the occupation probabilities of various shell model orbitals measured via the $(e, e'p)$ reaction are in considerable disagreement with the IPM (for an overview, see [1]). Moreover, using realistic interactions, the IPM fails to describe the binding energy of nuclei. This failure is a consequence of the strong short-range components of the interaction, which are necessary to reproduce NN data and which induce into the nuclear wave function correlations beyond the mean field description. Thus, a careful evaluation of short-range correlations (SRC) is needed to describe nuclear properties in terms of a realistic NN-interaction and to provide profound insight into the structure of the hadronic interaction in the nuclear medium [2]. SRC give an important contribution to the semi-inclusive $(e, e'p)$ reaction in the continuum, at high values of the missing energy well beyond the two-nucleon emission threshold, where, however, many other competing processes contribute and a clear identification of SRC appears very difficult. Thus, the most powerful and clear tool for a deeper investigation of SRC is the electromagnetically induced two-nucleon knockout since the probability that a real or a virtual photon is absorbed by a pair of nucleons should be a direct measure for the correlations between these nucleons [1, 3].

In general, two-nucleon knockout is a very challenging subject. Experimentally, the expected cross sections to be measured within a triple coincidence are exceedingly small. Only with the advent of high-duty-cycle electron beams like NIKHEF, MAMI or TJNAF a systematic investigation of this reaction has become possible. At present, only a few pioneering measurements have been carried out [4, 5, 6, 7], but the prospects are very encouraging [8, 9].

From a theoretical point of view, a comprehensive treatment of the nuclear many body problem of the initial state has to be performed and a profound knowledge of the relevant reaction mechanisms is necessary. In that context, one has to be aware of possible disturbing effects like contributions of two-body currents as well as of the final state interaction (FSI) between the two outgoing nucleons and the residual nucleus, whose good understanding is essential to disentangle and investigate short-range effects.

However, due to the complexity of the subject, several approximations have been performed in the past which restrict the reliability of the existing models (consider [1, 10, 11, 12, 13, 14, 15, 16, 17] and the references therein) with respect to the interpretation of the experimental data. In this

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context, one crucial assumption is the fact that the mutual interaction between the two outgoing nucleons, denoted as NN-FSI, can be neglected. Only the major contribution of FSI, due to the interaction of each of the two outgoing nucleons with the residual nucleus, was taken into account in the different models. The guess was that the effect of NN-FSI should not be large, at least in the superparallel kinematics, where the two nucleons are ejected back to back parallel and antiparallel to the momentum transfer. The superparallel kinematics is of particular interest for theoretical [18] and experimental [6, 19, 20] investigations, because in this kinematics a Rosenbluth L/T-separation makes it in principle possible to extract the longitudinal structure function, that is assumed to be most sensitive to SRC. A first calculation on nuclear matter [21] clearly indicates that NN-FSI can in general not be neglected, even in the superparallel kinematics. This result has been confirmed by our recent work [22, 23, 24] for two-nucleon knockout from a complex nucleus like ^{16}O within the unfactorized approach of [10]. The corresponding theoretical framework and the adopted approximations are outlined in section 2. Numerical results for some selected kinematical situations are presented in section 3. Some perspectives of possible improvements and future developments are given in section 4.

2. THE MODEL

The cross section for electromagnetic two-nucleon-knockout is given in general by the square of the scalar product of the relativistic electron current j^μ and of the nuclear current J^μ , where the latter is given by the Fourier transform of the transition matrix element of the charge-current density operator between initial and final nuclear states, i.e.,

$$J^\mu(\vec{q}) = \int \langle \Psi_f | \hat{J}^\mu(r) | \Psi_i \rangle e^{i\vec{q}\cdot\vec{r}} d\vec{r}. \quad (1)$$

The model is based on the two assumptions of an exclusive reaction, for the transition to a specific discrete state of the residual nucleus, and of the direct knockout mechanism, i.e., we assume a direct one-step process where the photon directly interacts with the pair of nucleons that are emitted and the A-2 nucleons of the residual nucleus behave as spectators.

As a result of these two assumptions, the integral (1) can be reduced to a form with three main ingredients: the two-nucleon overlap function (TOF) between the ground state of the target and the final state of the residual nucleus, the nuclear current \hat{J}^μ of the two emitted nucleons, and the two-nucleon scattering wave function $|\psi_f\rangle$.

In general, the nuclear current operator $\hat{J}^\mu(r)$ is the sum of a one-body and a two-body part (Fig. 1). The one-body part consists of the usual charge operator and the convection and spin currents. The two-body part consists of the nonrelativistic pionic seagull MEC, the pion-in-flight MEC and the Δ -contribution. For more details see [11, 25].

The TOF requires a calculation of the two-hole spectral function including consistently different types of correlations, i.e. SRC and tensor correlations (TC), as well as long-range correlations (LRC), which are mainly representing collective excitations of nucleons at the nuclear surface. SRC and TC are introduced in the radial wave function of the relative motion by means of state dependent defect functions which are added to the uncorrelated partial wave. For the pp-case [10, 26], the defect functions are obtained by solving the Bethe-Goldstone equation using the Bonn OBEPQ-A potential [27]. For the pn-case [12], SRC and TC correlations are calculated within the framework of the coupled-cluster method [2] with the AV14-potential [28] and using the so-called S_2 approximation, where only 1-particle 1-hole and 2-particle 2-hole excitations are included in the correlation operator. This method is an extension of the Bethe-Goldstone equation and takes into account, among other things and besides particle-particle ladders, also hole-hole ladders. These, however, turn out to be rather small in ^{16}O [2], so that the two approaches are similar in the treatment of SRC. LRC are included in the expansion coefficients of the TOF. For the pp-case, these coefficients are calculated in an extended shell-model basis within a dressed random phase approximation [10, 26]. For the pn-case, a simple configuration mixing calculation of the two-hole

states in ^{16}O has been done and only $1p$ -hole states are considered for transitions to the low-lying states of ^{14}N [12].

Concerning the treatment of the final state two-nucleon scattering function $|\psi_f\rangle$, we will discuss different approximations frequently used in the past. In the simplest approach any interaction between the two nucleons and the residual nucleus is neglected and a plane-wave (PW) approximation is assumed for the two outgoing nucleons. In the more sophisticated approach of [10] (DW), the interaction between each of the outgoing nucleons and the residual nucleus is considered by using a complex phenomenological optical potential V^{OP} for nucleon-nucleus scattering which contains a central, a Coulomb and a spin-orbit term [29] (see diagram (a) in Fig. 2). Only very recently the mutual NN-interaction between the two outgoing nucleons, called NN-FSI, has been taken into account [22, 23, 24], see diagram (b) in Fig. 2. Multiscattering processes like those depicted by diagrams (c) and (d) of Fig. 2 would require a genuine three-body approach which is presently under investigation. At the moment, these diagrams are neglected so that the results discussed in the next section must be considered as preliminary. The hope of the present approximation is to obtain a first reliable estimate of the role of NN-FSI in various kinematical situations for two-nucleon knockout from ^{16}O . The present treatment of incorporating FSI due both to the nucleon-nucleus interaction V^{OP} and to the mutual NN-interaction V^{NN} is denoted by DW-NN. In addition, we denote PW-NN the treatment where only V^{NN} is considered and V^{OP} is switched off.

In a more quantitative form, denoting $|\vec{p}_i^0\rangle$ a plane-wave state of nucleon i , with momentum \vec{p}_i^0 , and by $|\phi^{OP}(\vec{p}_i^0)\rangle$ the state of nucleon i distorted by the optical potential according to the Schrödinger equation

$$\left(H_0(i) + V^{OP}(i)\right) |\phi^{OP}(\vec{p}_i^0)\rangle = E_i |\phi^{OP}(\vec{p}_i^0)\rangle, \quad (2)$$

where $H_0(i)$ denotes the kinetic energy operator, the corresponding final states in these different approximations are given by

$$|\psi_f\rangle^{PW} = |\vec{p}_1^0\rangle |\vec{p}_2^0\rangle, \quad (3)$$

$$|\psi_f\rangle^{DW} = |\phi^{OP}(\vec{p}_1^0)\rangle |\phi^{OP}(\vec{p}_2^0)\rangle, \quad (4)$$

$$|\psi_f\rangle^{PW-NN} = |\vec{p}_1^0\rangle |\vec{p}_2^0\rangle + G_0(z) T^{NN}(z) |\vec{p}_1^0\rangle |\vec{p}_2^0\rangle. \quad (5)$$

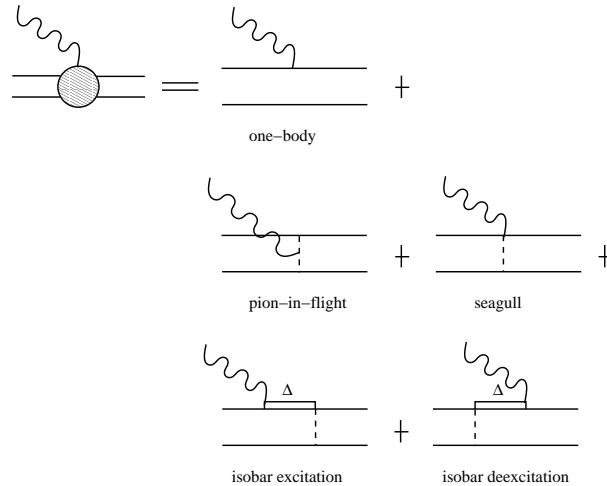


FIG. 1: The electromagnetic current contributions taken into account in the present approach.

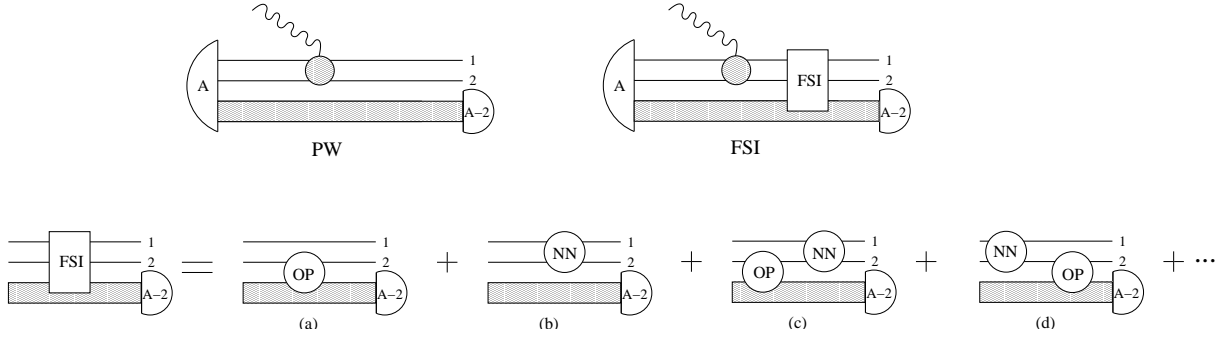


FIG. 2: The relevant diagrams for electromagnetic two-nucleon knockout on a complex nucleus A. The two diagrams on top depict the plane-wave approximation (PW) and the distortion of the two outgoing nucleon wave functions by final state interactions (FSI). Below, the relevant mechanisms of FSI are depicted in detail, where the open circle denotes either the nucleon-nucleus scattering amplitude (OP), or the nucleon nucleon-scattering amplitude (NN), see equation (6). Diagrams which are given by an interchange of nucleon 1 and 2 are not depicted. In the present approach, only diagrams (a) and (b) are taken into account.

In the last equation, the NN-scattering amplitude T^{NN} is given by $(z = \frac{(\vec{p}_1^0)^2}{2m_p} + \frac{(\vec{p}_2^0)^2}{2m_p} + i\epsilon)$

$$T^{NN}(z) = V^{NN} + V^{NN}G_0(z)T^{NN}(z), \quad (6)$$

with the free propagator

$$G_0(z) = \frac{1}{z - H_0(1) - H_0(2)}. \quad (7)$$

Moreover, our full approach DW-NN is given by

$$|\psi_f\rangle^{DW-NN} = |\phi^{OP}(\vec{p}_1^0)\rangle |\phi^{OP}(\vec{p}_2^0)\rangle + G_0(z)T^{NN}(z)|\vec{p}_1^0\rangle |\vec{p}_2^0\rangle. \quad (8)$$

In our practical calculations, the NN-scattering amplitude T^{NN} is evaluated with the help of a usual partial wave decomposition of the NN-interaction V^{NN} taking into account all contributions up to an orbital angular momentum of 3, i.e., the isospin-1 partial waves $^1S_0, ^3P_0, ^3P_1, ^3P_2, ^1D_2, ^3F_2, ^3F_3$, and 3F_4 contributions for pp-knockout and moreover the isospin-0 contributions $^3S_1, ^1P_1, ^3D_1, ^3D_2, ^3D_3$, and 1F_3 for pn-knockout. It has been checked that this truncation is sufficient at least for the kinematics considered in this paper. More details concerning the numerical implementation of the NN-FSI can be found in [23].

3. RESULTS

In this section, we discuss the role of NN-FSI on different electromagnetic reactions in various kinematics. We start with the superparallel kinematics of a recent Mainz experiment [6]. The differential cross sections calculated within the different approximations (3-5, 8) for the $^{16}\text{O}(e, e'pp)$ reaction to the 0^+ ground state of ^{14}C and the $^{16}\text{O}(e, e'pn)$ reaction to the 1^+ ground state of ^{14}N are displayed in the left and right panels of Fig. 3, respectively. It can be clearly seen in the figure that the inclusion of the optical potential leads, in both reactions, to an overall and substantial reduction of the calculated cross sections (see the difference between the PW and DW results), which, e.g. at $p_B = 100$ MeV/c, corresponds to a factor of ~ 0.2 in $(e, e'pp)$ and of ~ 0.3 in $(e, e'pn)$. This effect is well known and it is mainly due to the imaginary part of the optical

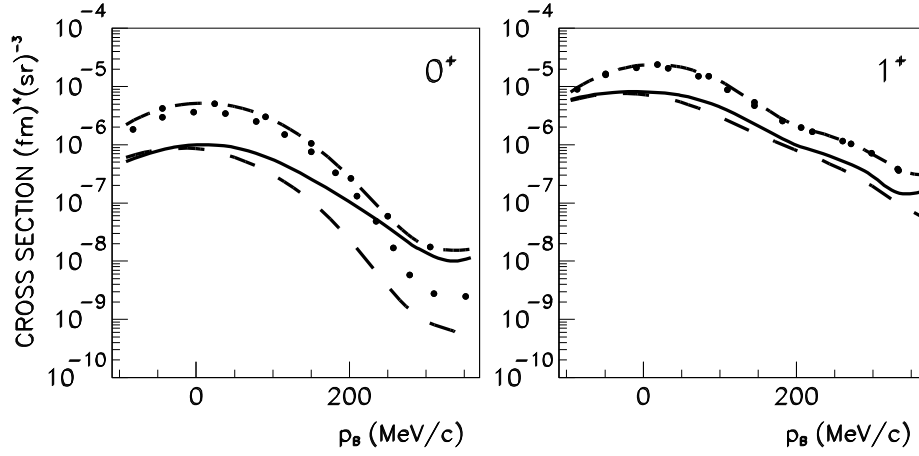


FIG. 3: The differential cross section of the $^{16}\text{O}(e, e'pp)$ reaction to the 0^+ ground state of ^{14}C (left panel) and of the $^{16}\text{O}(e, e'pn)$ reaction to the 1^+ ground state of ^{14}N (right panel) in a superparallel kinematics with an incident electron energy $E_0 = 855$ MeV, an electron scattering angle $\theta_e = 18^\circ$, energy transfer $\omega = 215$ MeV and $q = 316$ MeV/c. In $^{16}\text{O}(e, e'pn)$ the proton is ejected parallel and the neutron antiparallel to \vec{q} . Different values of p_B are obtained changing the kinetic energies of the outgoing nucleons. Positive (negative) values of p_B refer to situations where \vec{p}_B is parallel (anti-parallel) to \vec{q} . Line convention: PW (dotted), PW-NN (dash-dotted), DW (dashed), DW-NN (solid).

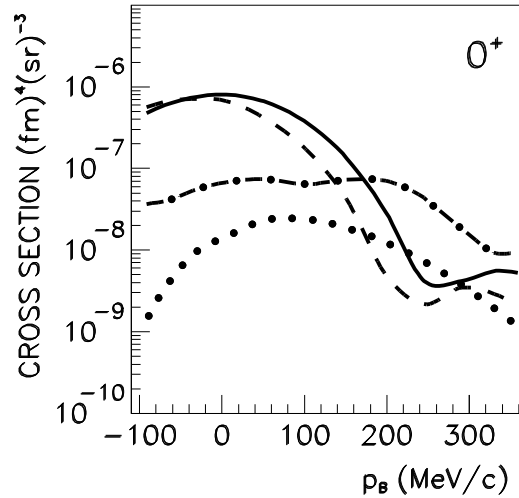


FIG. 4: The differential cross section of the $^{16}\text{O}(e, e'pp)$ reaction to the 0^+ ground state of ^{14}C in the same superparallel kinematics as in Fig. 3. Line convention: DW with the Δ -current (dotted), DW-NN with the Δ -current (dash-dotted), DW with the one-body current (dashed), DW-NN with the one-body current (solid).

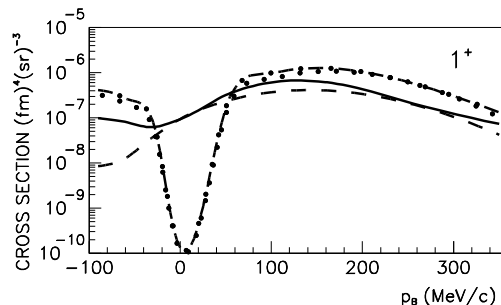


FIG. 5: The differential cross section in the $^{16}\text{O}(e, e'pp)$ reaction to the 1^+ state of ^{14}C for the superparallel kinematics discussed in the text. Line notation as in Fig. 3.

potential, that accounts for the flux lost to inelastic channels in the nucleon-residual nucleus elastic scattering. The optical potential gives the dominant contribution of FSI for recoil-momentum values up to $p_B \simeq 150$ MeV/c. At larger values NN-FSI gives an enhancement of the cross section, that increases with p_B . In $(e, e'pp)$ this enhancement goes beyond the PW result and amounts to roughly an order of magnitude for $p_B \simeq 300$ MeV/c. In $(e, e'pn)$ this effect is still sizeable but much weaker, i.e. only 50% of enhancement at $p_B = 300$ MeV/c.

It can be seen from Fig. 4, that the substantial increase of the cross section in pp-knockout at large missing momenta is mainly due to a strong enhancement of the Δ -current contribution by NN-FSI. Up to about 100-150 MeV/c, however, this effect is completely overwhelmed by the dominant contribution of the one-body current, while for larger values of p_B , where the one-body current is less important in the cross section, the increase of the Δ -current is responsible for the substantial enhancement in the final result of Fig. 3. The effect of NN-FSI on the one-body current is anyhow sizeable (a factor of about 2 at $p_B = 100$ MeV/c), and it is responsible for the NN-FSI effect at lower and intermediate values of p_B in Fig. 3.

As has been outlined in [23], the main difference concerning the role of NN-FSI in pp- and pn-emission is that in the latter reaction the seagull current, which is not present in pp-emission, is also largely affected by NN-FSI. It turns out that the strong effects of NN-FSI on the Δ -contribution and on the seagull current tend to cancel each other to a large extent, so that the corresponding pn-cross section is only moderately affected. It should be stressed that we have found such a cancellation in pn-emission only for the unpolarized cross section in the superparallel kinematics, which is, however, a situation of particular experimental interest. We did not check till now if a similar cancellation occurs for other kinematics or in polarization observables.

Another important result of our studies is that the role of NN-FSI depends strongly of the specific state of the residual nucleus. In general, for the kinematics studied so far in pp-knockout, it turns out that the 1S_0 relative state of the pp-pair in the target is more affected by NN-FSI than the higher partial waves. It is known from previous work [10] that the 1S_0 state dominates the $^{16}\text{O}(e, e'pp)$ cross section to the 0^+ ground state of ^{14}C . Thus, the strong effect of NN-FSI found for this transition is not surprising. On the other hand, for the transition to the 1^+ excited state, where the 1S_0 partial wave in the initial state cannot contribute, it is shown in Fig. 5 that the effect of NN-FSI becomes considerably smaller, but anyhow not negligible.

At next, we turn to photoinduced pp-knockout. The cross section of the $^{16}\text{O}(\gamma, pp)$ reaction to the 0^+ ground state of ^{14}C calculated with the different approximations for FSI is shown in Fig. 6. The separated contributions of the one-body and Δ -currents in DW and DW-NN are displayed in Fig. 7. Calculations have been performed in superparallel kinematics, and for an incident photon energy which has the same value, $E_\gamma = 215$ MeV, as the energy transfer in the $(e, e'pp)$ calculation

of Fig. 3. This kinematics, which is not very well suited for (γ, pp) experiments, is interesting for a theoretical comparison with the corresponding results of the electron induced reaction in Figs. 3 and 4. In general, two-body currents give the major contribution to (γ, NN) reactions. In this superparallel kinematics, however, the (γ, pp) cross section is dominated by the one-body current for recoil momentum values up to about 150 MeV/c. For larger values the Δ -current plays the main role. This is the same behavior as in the corresponding situation for $(e, e'pp)$. Similar to $(e, e'pp)$, NN-FSI produces an enhancement of the Δ -current contribution, see Fig. 7, whose absolute size strongly depends on p_B . Whereas for $p_B = 50$ MeV/c, the effect is only $\sim 70\%$, one obtains more than one order of magnitude of enhancement at $p_B = -100$ MeV/c. The role of NN-FSI on the one-body current is practically negligible in (γ, pp) , while it is significant in $(e, e'pp)$ as has been discussed above. This effect is produced in $(e, e'pp)$ on the longitudinal part of the nuclear current, that does not contribute in reactions induced by a real photon. Thus, in practice, in this kinematics NN-FSI affects only the Δ -current and therefore in Fig. 6 its effect is negligible in the region where the one-body current is dominant. At large values of p_B , where the role of the Δ -current becomes important, the enhancement produced by NN-FSI is large, i.e. a factor of ~ 4 at $p_B = 300$ MeV/c, but nevertheless weaker than in the same superparallel kinematics for $(e, e'pp)$.

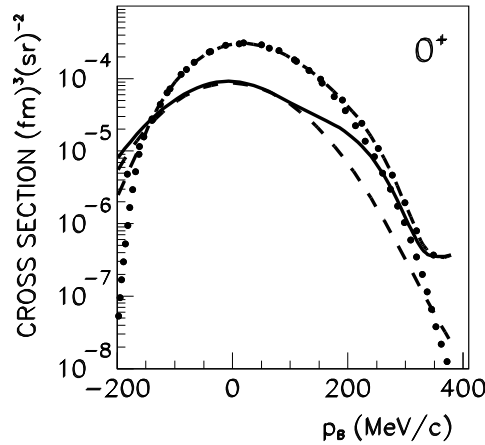


FIG. 6: The differential cross section of the $^{16}\text{O}(\gamma, pp)$ reaction to the 0^+ ground state of ^{14}C in superparallel kinematics at $E_\gamma = 215$ MeV. Line convention as in Fig. 3.

Another example is presented in Fig. 8, where the results of the different approximations in the treatment of FSI are displayed for the $^{16}\text{O}(\gamma, pp)$ reaction to the 0^+ ground state of ^{14}C (left panel) and for the $^{16}\text{O}(\gamma, pn)$ reaction to the 1^+ ground state of ^{14}N (right panel) in a coplanar kinematics at $E_\gamma = 120$ MeV, where the energy and the scattering angle of the outgoing proton are fixed at $T_1 = 45$ MeV and $\gamma_1 = 45^\circ$, respectively. Different values of the recoil momentum can be obtained by varying the scattering angle γ_2 of the second outgoing nucleon on the other side of the photon momentum. It can be clearly seen in the figure that NN-FSI has almost no effect. In contrast, a very large contribution is given, for both reactions, by the optical potential, which produces again a substantial reduction. This kinematics, which appears within reach of available experimental facilities, was already envisaged in [14] as promising to study SRC in the (γ, pp) reaction. In fact, at the considered value of the photon energy, the contribution of the Δ -current is relatively much less important, and while the (γ, pn) cross section is dominated by the seagull current [14], in the

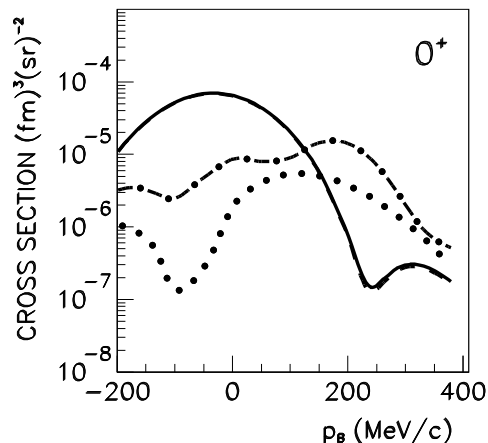


FIG. 7: The differential cross section of the $^{16}\text{O}(\gamma, pp)$ reaction to the 0^+ ground state of ^{14}C in the same kinematics as in Fig. 6. Line convention as in Fig. 4.

(γ, pp) cross section the contribution of the one-body current is large and competitive with the one of the two-body current. This can be seen in Fig. 9, where the two separated contributions are shown in the DW and in the DW-NN approximations. Both processes are important: the Δ -current plays the main role at lower values of γ_2 , while for $\gamma_2 \geq 110^\circ$ the one-body current and therefore SRC give the major contribution. The effect of NN-FSI is practically negligible on both terms, which explains the result in the final cross section of Fig. 8. A study of the (γ, pp) reaction in a kinematics of the type considered in Figs. 8 and 9, where NN-FSI is negligible and correlations are important, might represent a promising alternative to the $(e, e'pp)$ reaction for the investigation of SRC.

4. SUMMARY AND OUTLOOK

Exclusive experiments with direct two-nucleon emission by an electromagnetic probe have been suggested a long time ago as good candidates to study correlations beyond a mean field description of nuclei. The study of these reactions is very challenging both for experiment and theory. Only the presently available high-duty cycle accelerators allow the corresponding measurements of the exceedingly small cross sections. First experiments have already been performed or are presently under investigation. From a theoretical point of view, a good understanding of the relevant reaction mechanisms is necessary for the interpretation of the data. In that context, disturbing effects like the role of two-body currents or final state interactions (FSI) must be well under control. Concerning FSI, a consistent evaluation would require a three-body approach for the two nucleons and the residual nucleus. So far, only the major contribution of FSI, due to the interaction of each of the two outgoing nucleons with the residual nucleus, was taken into account in the different models. The original guess was that the mutual interaction between the two outgoing nucleons (NN-FSI) could be neglected.

In the present work, we have studied the role of NN-FSI within a perturbative treatment which should give a first reliable idea of their relevance. It turns out that NN-FSI are in general not negligible. However, their absolute size strongly depends on the chosen kinematics, on the type

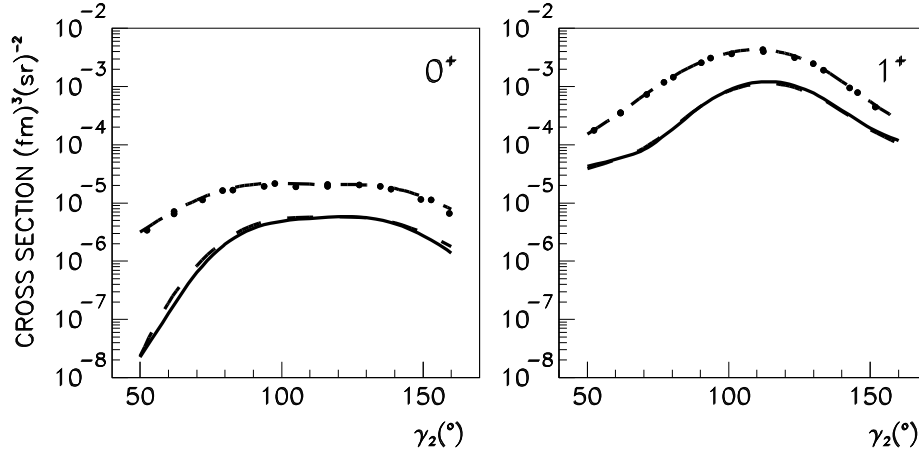


FIG. 8: The differential cross section of the $^{16}\text{O}(\gamma, pp)$ reaction to the 0^+ ground state of ^{14}C (left panel) and of the $^{16}\text{O}(\gamma, pn)$ reaction to the 1^+ ground state of ^{14}N (right panel) as a function of the scattering angle γ_2 of the second outgoing nucleon in a coplanar kinematics with $E_\gamma = 120$ MeV, $T_1 = 45$ MeV and $\gamma_1 = 45^{\circ}$. Line convention as in Fig. 3.

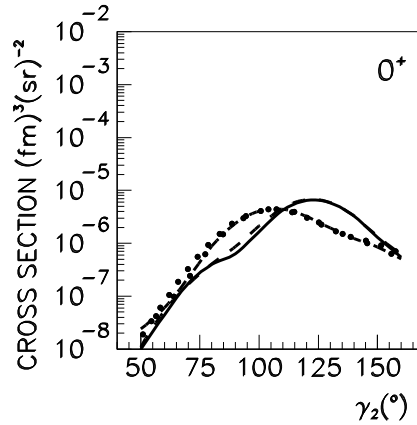


FIG. 9: The differential cross section of the $^{16}\text{O}(\gamma, pp)$ reaction to the 0^+ ground state of ^{14}C in the same kinematics as in Fig. 8. Line convention as in Fig. 4.

of reaction and on the final state of the residual nucleus. In the kinematics studied till now, NN-FSI effects are in general larger in pp- than in pn-knockout and in electro- than in photoinduced reactions. They affect in a different manner the various terms of the nuclear current, usually more the two-body than the one-body terms, and they are sensitive to the various theoretical ingredients of the reaction. This makes it difficult to make predictions about the role of NN-FSI in a particular

situation. Each specific situation should be individually investigated.

In order to improve the reliability of the theoretical description of the two-nucleon knockout process, the full three-body problem of the final state has to be tackled in forthcoming studies. In that context, special emphasis has to be devoted to a more consistent treatment of the initial and the final state.

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